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# Urban and Regional Built-up Analysis (URBA): Higher resolution (2.5m) of built-up detection GHSL Europe wall-to-wall (gap free) coverage

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# Table of Contents

# Introduction

In 2012 was conducted the first, big, heterogeneous, successful experiment on Optical High Resolution images that propose the GHSL as the new way to map, analyze and monitor human settlements [1][2]. In a few months, using a system, called IQ, were processed more than 15.000 satellite scenes with spatial resolution ranging between 0.5-10m from providers like: SPOT (2 and 5), CBERS-2B, RapidEye (2 and 4), WorldView (1 and 2), GeoEye-1, QuickBird-2, IKONOS-2.

That dataset was not covering the entire globe but give us the feeling of what means to process 24 million of square meter at high resolution. In 2013 a new dataset were made available and a new challenge was offered to the GHSL.

The new dataset is named Copernicus Core_003[3] and is made of around 3000 satellite scene and all of them have a resolution 2.5m. It perfectly fit with the new GHSL VHR method and because of the full coverage of Europe and the availability of 3 bands in all scenes it allows further research to improve.

In 2013 a specialization of the GHSL method has been started. After three years of improvements and 11 versions, we have come today to produce the highest resolution map with full coverage of all Europe.

Its name is European Settlement Map (ESM)[4]. The uniformity dataset has improved a lot the result obtained up to 2012, but to produce the wall-to-wall map is not just process images.

Gaps, clouds, and an acquisition one year long have created many headaches before coming to a complete map.

Some issues have been solved thanks to new provided images, for other we used a bit of imagination.

# DG REGIO requirements

In the context of an administrative arrangement between the Joint Research Centre and the Directorate General for Regional Policy (DG REGIO) on the built-up detection of human settlements in Europe, we were required to adapt the GHSL method and technology for the use of GHSL output in the European Urban Atlas, flagship project of DG REGIO.

The objective of this analysis is expected to contribute to the 6th Cohesion Report a tri-annual report on the economic, social and territorial cohesion. The GHSL output is expected to provide value to the chapter which covers trends in EU regions and territories, especially for what regards: i) the detection of smaller settlements, ii) the creation of a population grid using a disaggregation methodology, and iii) refinement of other European reference layers like CORINE LC.

Based on a methodology, developed by the European Commission and OECD, to identify cities with more than 50.000 inhabitants, the JRC has developed techniques to expand the classification of human settlements to smaller and medium-sized towns, which play an important role in rural and remote regions.

Finally the improvement of the population grid, a high priority for DG REGIO, as it provides the backbone of all the spatial analysis done in this context, has been made possible through the GHSL method for population disaggregation. The GHSL output has provided the frame for geo-spatialization of population data.

## The Improvement method "the workflows"

Because it is a typical practice in modelling and a because it was clear that the scene would come from the provider for at least in a couple of years, it was decided to adopt a workflow development method, where each improvement, tuning or new data is recorded and is given a new name to the process. A summary of all workflow is represented in Table 1

| Workflow version | Number of Steps | Number of Scenes | Time | Description (For report) |
|---|---|---|---|---|
| W1 | 8 | 37 | 18/03/2013 – 19/03/2013 | First prototype of the workflow. |
| W2 | 11 | 37 | 20/03/2013 | Second prototype of the workflow. Main improvement: improvement of the builtscale generation; Added: land mask. |
| W3 | 13 | 2271 | 19/04/2013 – 03/05/2013 | Main improvement: the builtscale generation; Added: the cloud mask. |
| W4 | 14 | 2275 | 03/05/2013 – 15/05/2013 | Main improvement: the builtscale generation, the cloud mask, and vegetation index. |
| W5 | 5 | 428 | 30/05/2013 – 31/05/2013 | Workflow optimisation: W04 has been optimised / ajusted. Processing the lacking scenes. |
| W6 | 1 | 2703 | 29/05/2013 – 31/05/2013 | Workflow optimisation: Additional treatment of the results of the W05 necessary to generate the optimised workflow final results. |
| W7 | 2 | 2582 | 18/11/2013 – 29/11/2013 | Workflow incorporation, 2.5 meter resolution output with classification (0,1,2,3,4,5), post processing to 10 meter resolution |
| W8 | 2 | 10 | 18/11/2013 – xx/12/2013 | Workflow incorporation, 2.5 meter resolution TEST output with classification (0,1,2,3,4,5), post processing to 2.5 meter resolution (experimental) |
| W9 | 2 | 2994 | 11/03/2014 | Two line of workflow incorporation, 2.5 meter resolution output with classification (0,1,2,3,4,5), post processing to 10 meter resolution with zoning |
| W10 | 2 | 3143 | 07/04/2014 | Two line of workflow incorporation, 2.5 meter resolution output with classification (0,1,2,3,4,5), post processing to 10 meter resolution with zoning V2 |
| W11 | 2 | 3601 | 11/08/2014 | Three line of workflow incorporation, 2.5 meter resolution output with classification (0,1,2,3,4,5), post processing to 10 meter resolution with zoning V3 |

*Table 1 - Workflows*

### *The GHSL Workflow (W1)*

The first experiment, the W1 is the modular version of the GHSL 2012. The GHSL 2012 was spitted in 8 modules which correspond to its main step. On March 2013 it processed 37 scenes.

### *The GHSL Workflow (W2)*

In the second experiment were added the layer Corinne Land Cover (CLC) as land mask and a new intermediate product named BuiltScale. The BuiltScale appearance is similar to the Saliency, but the value represents the square meter of a building. These improvements need 3 additional steps. The W2 executed in March processed the same 37 scene processed with the W1.

### *The GHSL Workflow (W3)*

By the mid of April 2013 we got the first big stock of 2271 images. The visual inspection of some of them showed presence of clouds over important cities like Milano (IT) and in a few cases over big region like in Canterbury (UK). Because of that were developed a specific algorithm to detect cloud and remove them from the images. After 15 days we got the first uncompleted big mosaic of 2271 scenes.

### *The GHSL Workflow (W4)*

The W4 is the final result of a research in optimization and tuning of procedure and parameters. It has been completed in the mid of May 2013 and it processed 2275 scenes. The W4 included vegetation detection through a pseudo NDVI joined and integrated with morphological procedure. The W4 is the biggest modular workflow with 14 modules detailed with their parameter in the technical report: 'GHSL for Copernicus SPOT-5 data, 2013'[5]. The GHSL model observed from its intermediate output can be described and explained using the following images:

*Figure 1 - Spot 2.5m false color*

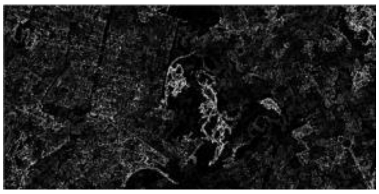


*Figure 2 - lum*

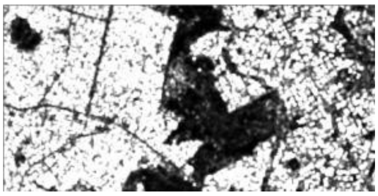


*Figure 3 - ptx*

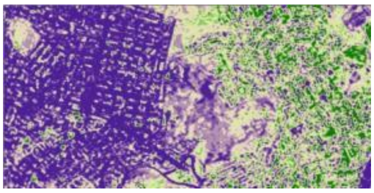


*Figure 4 - ndvix*

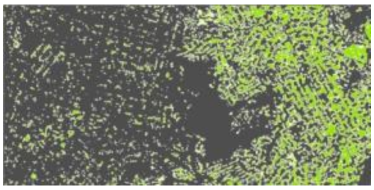


*Figure 5 - veg*

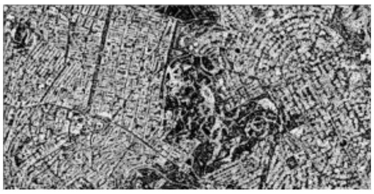


*Figure 6 - mrphCharact*

*Figure 7 - mrphSaliency*

*Figure 8 - bumorph*

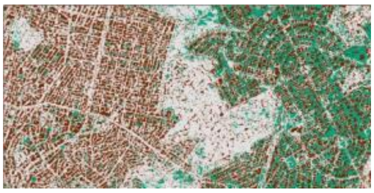


*Figure 9 - class*

*Figure 10 - buscale*

In figure 2 the input, a SPOT5 false colors image, in figure 3 the luminance (lum) which identifies the most shining area in the optical domain, it is extracted considering the collection of optical bands (β):

$$\mathrm{lum} = \max(\beta)\,,\beta = (\beta_1, \beta_2, \ldots\ldots, \beta_n)$$

In figure 4 the PANTEX [6], an edge/corner detection invented at the JRC which estimates the probability of an aggregation of pixel to be built-up derived from the lum. In figure 5 and 6 the new radiometric module of the pseudo NDVI and derived vegetation. From 6 to 9 the outputs of the morphological decomposition of the image (CSL)[7] which gives the building shape. The figure 10 is the building size characterization. In figure 11 the classification, fusion of all the intermediate information into one dataset.

### *The GHSL Workflow (W5)*

The W5 processed new 428 scenes arrived by the end of May, it let increase the dataset up to 2700 Images.

### *The GHSL Workflow (W6)*

The modular approach, undertaken until the W5, allowed the fine tuning of each step in the long chain of processing. With the W6 all the modules were joined into one, re-engineering the code form the beginning, optimizing the memory usage and reviewing the flow structure. The W6 is the W5 compressed and optimized in 1 module.

### *The GHSL Workflow (W7)*

The GHSL output is a classified raster with resolution 2.5m named class (see figure 11). It has six category values grouped in two groups (built up area - not built up area). The values are: 0, 1, 2, 3, 4, 5.
The values 5, 4, 3 are categories of the built up areas (blue); the values 0, 1, 2 are the categories of the non-built up (grey) (see figure 11).

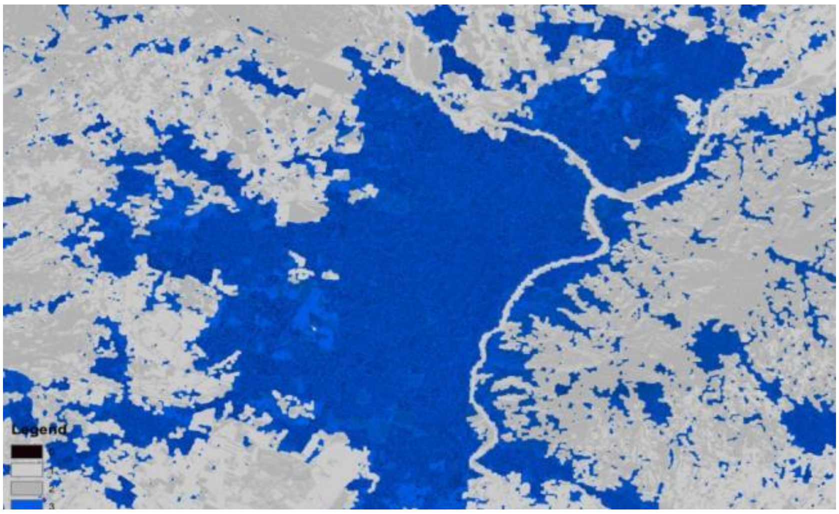



*Figure 11 - GHSL built up / not-built up*

Beside the built up area - not built up area classification, mapping all the values with specific colour we can represent our environment in a more complete way (see figure 12).

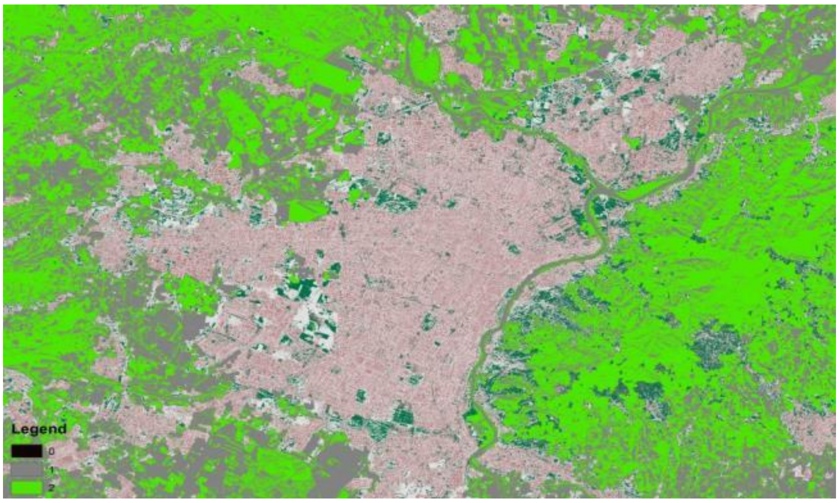



*Figure 12 - GHSL Classification*

Inside the built up area, the values 5, 4, 3 are respectively:
5. The buildings;
4. The urban green (the green in the built up);
3. Urban open space (not buildings, not green, in the built up area).
Outside the built up area is the not built up area which includes the values 2, 1, 0:
2. Vegetation out of the built up area;
1. Terrain, mountain, streets;
0. No data

The Outputs, that look very detailed and accurate in figure 11 and figure 12, are represented in map at scale 1:60.000. Zooming-in at the raster resolution, objects like cars or trucks, railways are classified as building (see figure 13). To overcome these issue in the W7 was introduced a post-processing script to clean and aggregate the output to a higher resolution.

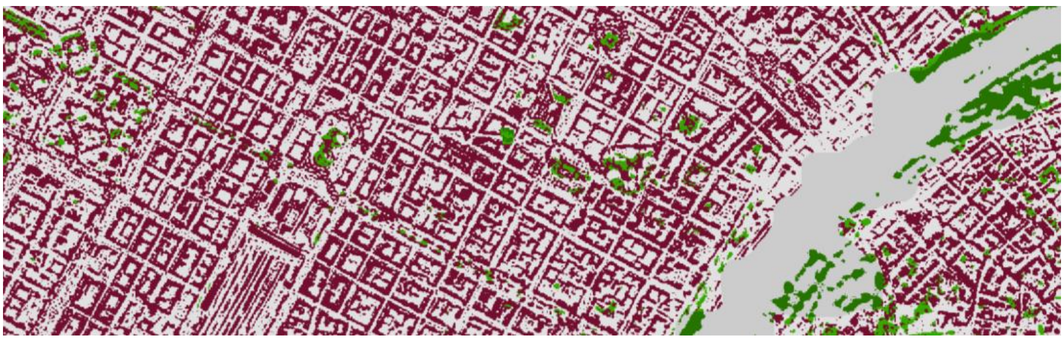


*Figure 13 - GHSL Classification at raster resolution*

In the post processing script the value 5 (buildings) are extrapolated from the dataset. Using the OSM reference street layer were cleaned the streets and the result were aggregated to 10 meter. The aggregation was made using an average operator. Because an aggregated cell of 10m layer corresponds to 4 x 4 cells of the 2.5 m were used the average operator that maintains the result compatible with the source. The result after the aggregation maintained a good detail (see figure 14) and thanks to the cleaning the accuracy increased.

*Figure 14 - GHSL Aggregated to 10m and cleaned*

### *The GHSL Workflow (W8)*

The W8 was a test of post processing with output at 2.5m. That test produced promising results in dense built-up, where a lot of external data can be used as reference, but more research is required to get good accuracy wall to wall in Europe. A good example that integrates the vector layer of Urban Atlas is in figure 15.

*Figure 15 – W8 test of post processing at 2.5m*

### The GHSL Workflow (W9)

During the first validation test in large areas (region Toscana) was measured a big over detection in rural areas. The morphological operator that was correctly detecting big building (industrial building) in city, in rural area was producing big errors of commission. In March 2014 all the scenes were processed again lowering the parameter that permits to detect industrial building. From that date on we had 2 dataset; one for the urban area and one for the rural. The two dataset are joined in the post processing. The post processing of the W9, like the one of the W8 and W7, cleans the streets and now also by applying urban-rural zooning merges the two line of processing.

### The GHSL Workflow (W10)

In April 2014 new images joined the dataset thus overcoming the 3000 images processed with the two parameter set generates 6286 scenes.

### The GHSL Workflow (W11)

Analysed the W10 was also found specific effects of extended over detection due to artificial plantations of olive trees (which create a regular pattern similar to a city) particularly in Spain. The railways initially used to eliminate some errors on the tracks, have also produced an undesired effect the

removal of building stations. Observing the results were found other errors of over detection in areas with fruit trees and berry plantations, beaches, dunes, sands and bare rocks.
As opposed important effects of omissions was detected in Spain in the city of Jae'n (see figure16).

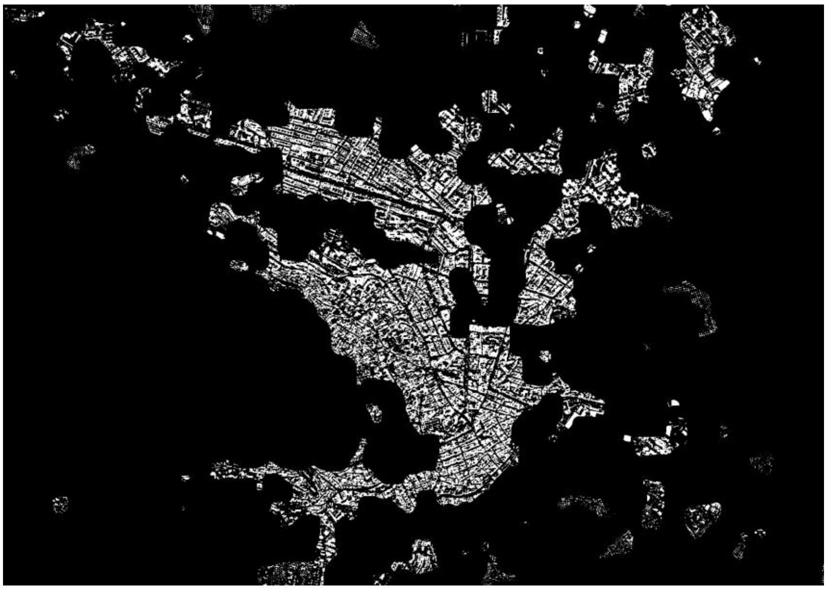


*Figure 16 – Erosion effect in Jaen (Spain)*

Of all the problems highlighted easy to describe, understand and detectable, however the under-detection in Jae'n has aroused concern. The under-detection found in the Spanish city is presented as a part of the erosion area outskirts of the city and creeps toward the center. The severity of this under-detection is particular because it reduces the detection of the city up in its densest area. The study of the problem has identified the problem in the size of the standardization window (3000x3000 pixels) which is used to standardize the values of Pantex obtained in the various zones of image respect to the layer of reference. The characteristic of some Spanish cities to be concentrated with very little sprawl and often isolated in the middle of a large area of bare ground combined with a large standardization window has resulted in an underestimate of the town focused.
Tests on a smaller standardization window (100x100) have been showing to solve the problem by providing a better estimation of the local built-up density. This solution has led to the realization of a third line workflow characterized by a small standardization window (see figure 17).

*Figure 17 - Erosion effect mitigated by a 100x100 standardization window*

The over detection caused by the fruit trees, berry plantations, olive groves, beaches, dunes, sands, rocks and bare was mitigated by using the reference layer CLC (Corine Land Cover) that distinguishes these areas with a resolution of 100m. The built-up pixels were compared with the CLC reference layer and if they are in the above categories, the value of built-up is set to zero. The use of the railways initially introduced in the W10 to remove the rails, was initially removed because it cancelled the building stations and built-up close the subways. Subsequently the railways dataset was updated downloading the latest version from OpenstreetMap including all the attributes. The new railway dataset classified accordingly to its new attributes were later reintroduced in the processing.

# The Update

During the 2014 monitoring, acquisition and processing of new images continued as described in the summary table figure 18. For each new captured image was applied the W11 with its 3 lines of processing plus post processing. In August, we have suspended the acquisition to proceed mosaicking and analysis of gaps.

| WORKFLOW Acquisition Images | | | | | |
|---|---|---|---|---|---|
| ESA | CID ftp | CID db | IQ db | IQ processing | |
| 3174 | 746 | 8 | 0 | 1 | 16/01/2013 |
| 3174 | 746 | 744 | 0 | 1 | 18/01/2013 |
| 3174 | 746 | 744 | 0 | 1 | 28/01/2013 |
| 3174 | 2546 | 744 | 0 | 1 | 06/02/2013 |
| 3174 | 2546 | 744 | 0 | 1 | 13/02/2013 |
| 3174 | 2546 | 2546 | 0 | 1 | 21/02/2013 |
| 3174 | 2546 | 2546 | 0 | 1 | 06/03/2013 |
| 3174 | 2546 | 2546 | 0 | 1 | 08/03/2013 |
| 3174 | 2546 | 2546 | 0 | 1 | 14/03/2013 |
| 3174 | 2546 | 2546 | 0 | 1 | 27/03/2013 |
| 3174 | 2726 | 2726 | | 1 | 23/04/2013 |
| 3174 | 2726 | 2726 | 2726 | 2268 | 16/05/2013 |
| 3174 | 2722 | 2722 | 2722 | 2268 | 28/05/2013 |
| 3174 | 2742 | 2742 | 2742 | 2742 | 06/06/2013 |
| 3174 | 2742 | 2742 | 2742 | 2651 | 10/06/2013 |
| ? | 2975 | 2582 | 2582 | 2582 | 30/01/2014 |
| ? | 3144 | ? | ? | 2994 | 11/03/2014 |
| ? | 3644 | ? | ? | 3143 | 07/05/2014 |
| | 3826 | ? | ? | 3601 | 11/08/2014 |

*Figure 18 - Scenes acquisition*

### *Datatype distribution (Spot 5 and Spot 6)*

The processed images are all from the sensor SPOT, 87% are SPOT5 the remaining are SPOT6. The geographical distribution of the images SPOT6 (in blue) is concentrate in the northern regions of Europe, while the remaining is SPOT5 (green)

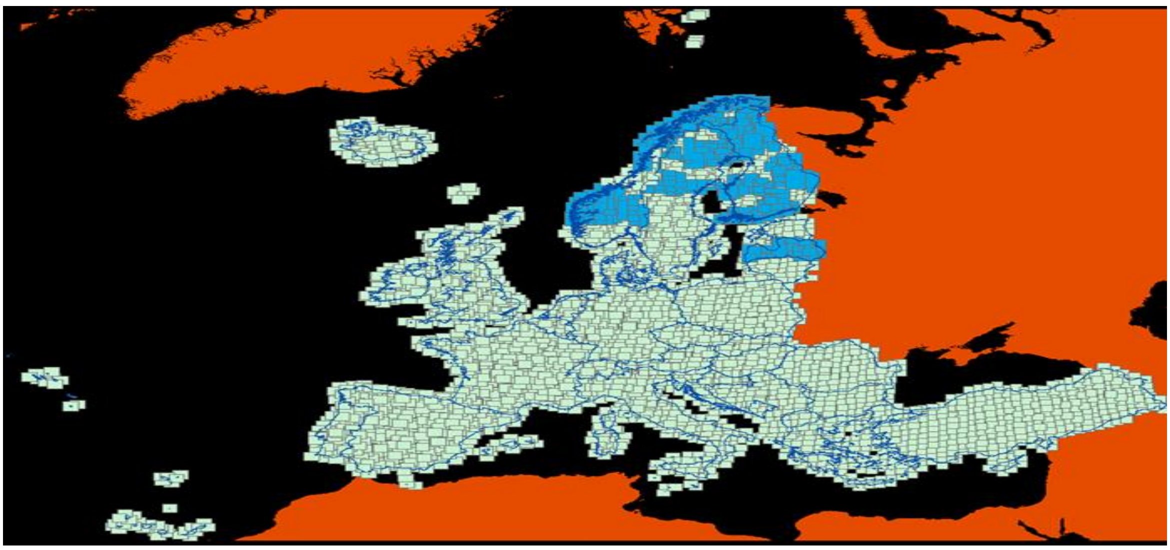


*Figure 19 - SPOT 5, SPOT 6 Geographical distribution*

In total, the images acquired and processed successfully are 3599, of which 3143 SPOT5, 456 SPOT6. The images belongs to the years 2010, 2011, 2012 and 2013

In detail:
21 images of 2010 (~1%)
2296 images of 2011 (~64%)
682 images of 2012 (~19%)
600 images of 2013 (~17%)

In figure 20 the geographical distributions of the images in the different years.

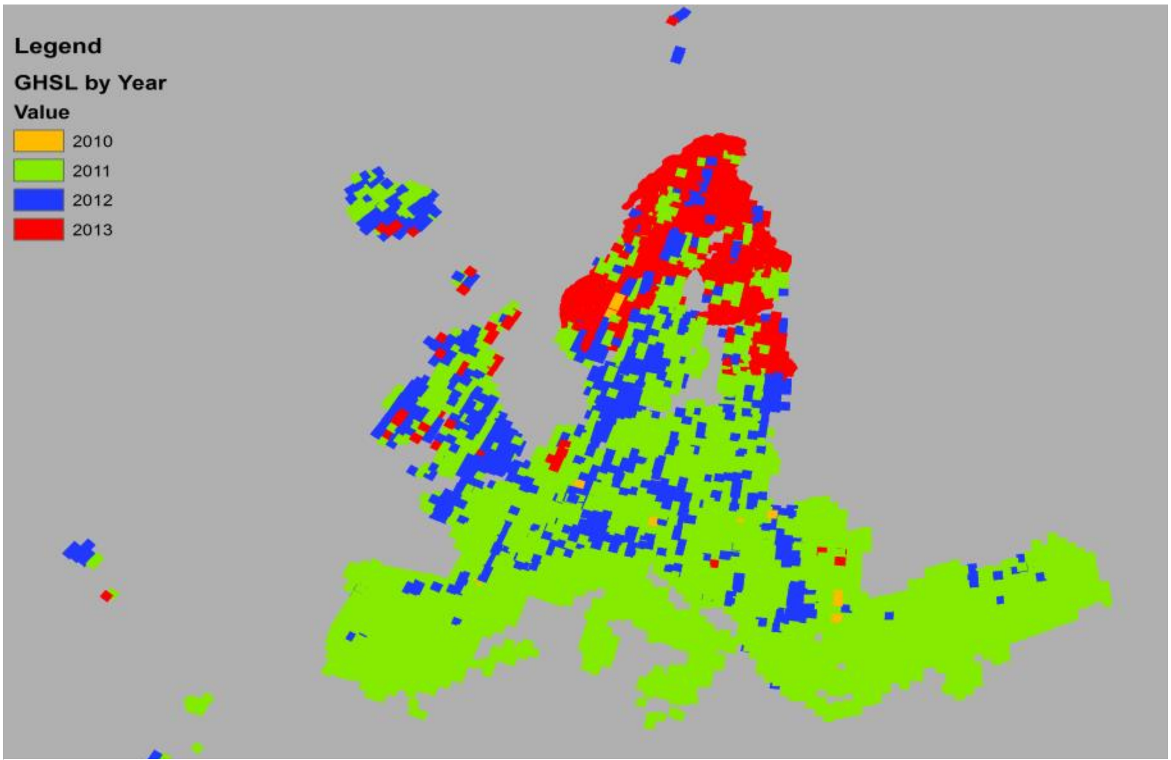



*Figure 20 - Scenes by year*

## The complete coverage

The complete coverage or wall to wall coverage is a thorny subject in remote sensing. Satellites, which fly outside the atmosphere, often have obscured their view from clouds. Clouds influenced remote sensing application in the algorithm because of their luminescence and influence the data acquisition management.

Figure 22 shows the map of the footprint of each captured image that covers the entire European regions subject to analysis.

*Figure 22 - Area covered*

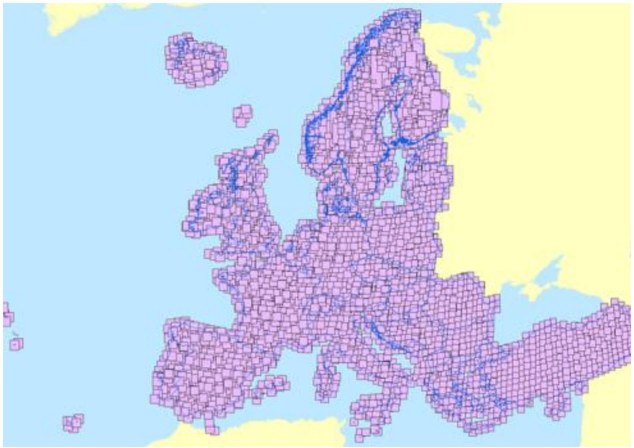


*Figure 21 - Scenes footprint*

### *The "gaps" issue*

Although the footprint of the map in Figure 21 shows a complete coverage of Europe, the data (the valid numerical values) contained in it are not as complete. The presence of clouds and numerous pixels in the images of no data reduce the amount of information extractable from them, leaving some areas not determined, not classifiable.
In Figure 23 the satellite picture of the urban area of the city of Milan and hinterland. In the image are visible the clouds and large areas of absence of data (blacks triangles) around the image that are part of the image and are result of a warping processing made by the provider.

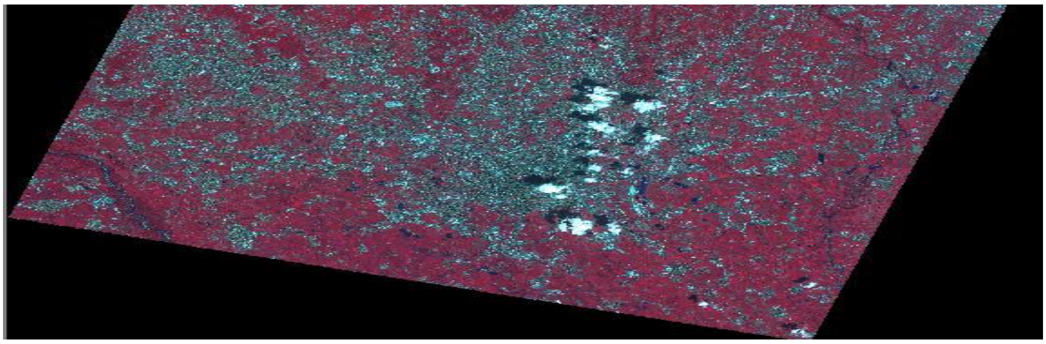


*Figure 23 - Clouds in source scene of Milano*

## *The cloud issue*

By working with satellite images, because of the altitude at which the images are acquired, the problem of the clouds is a typical noise in the analysis and extraction of information content. Because of the reflectance characteristics the clouds disturb the algorithms. They increase the average values of the pixels in the image and create areas with high contrast between the edge of the cloud and land. For these reasons was created a script for the removal of clouds. The script replaces the pixel values of the clouds with no data values. in figxx examples of extensive areas covered by clouds.

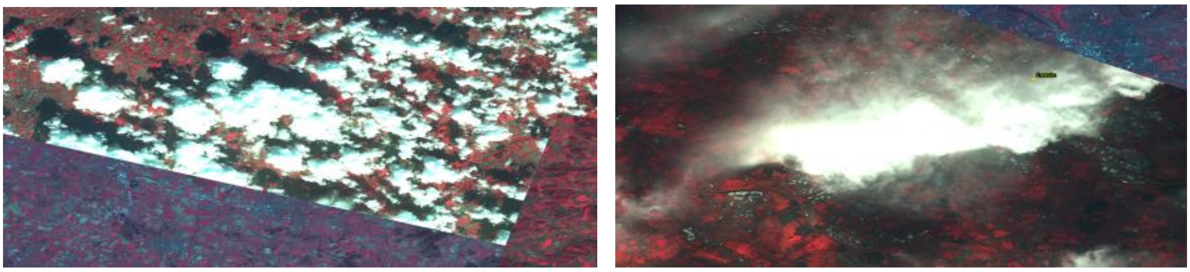


*Figure 24 – Diffuse clouds*

## *The extent of the problem*

The total extent of cloud cover compared to the entire study area (the Europe) is of particular importance to stand at 0.2%, but to produce detailed models (analysis of urban patterns in urban and rural areas), it is necessary to establish an accurate and complete. For example, in Italy in Lombardy clouds obscure part of the historic center of Milan. It is clear that this gap, placed at important points, adversely affects accuracy in any model you want to achieve. Following the last data acquisition in August, the number of gaps detected is 3,400 with a variable size ranging from 1 up to 741 km2 for a total of 17 086 km2 respect to the surface that European calculated on the basis of the GHSL 100m NUTS of 5,758,513 km2, it represent the 0.2%. In Figure 25 in red a representation of the clouds (it has been emphasized for visibility).

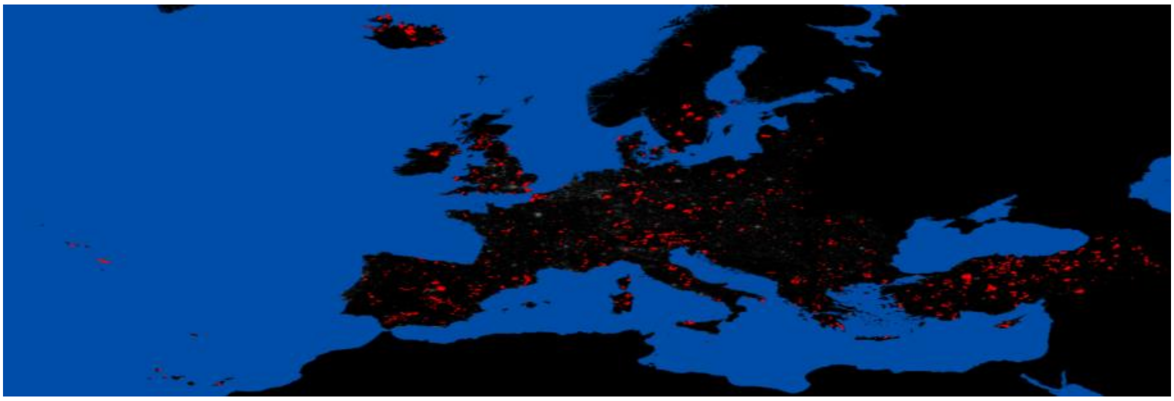


*Figure 25 - Cloud location*

### *Gaps analysis*

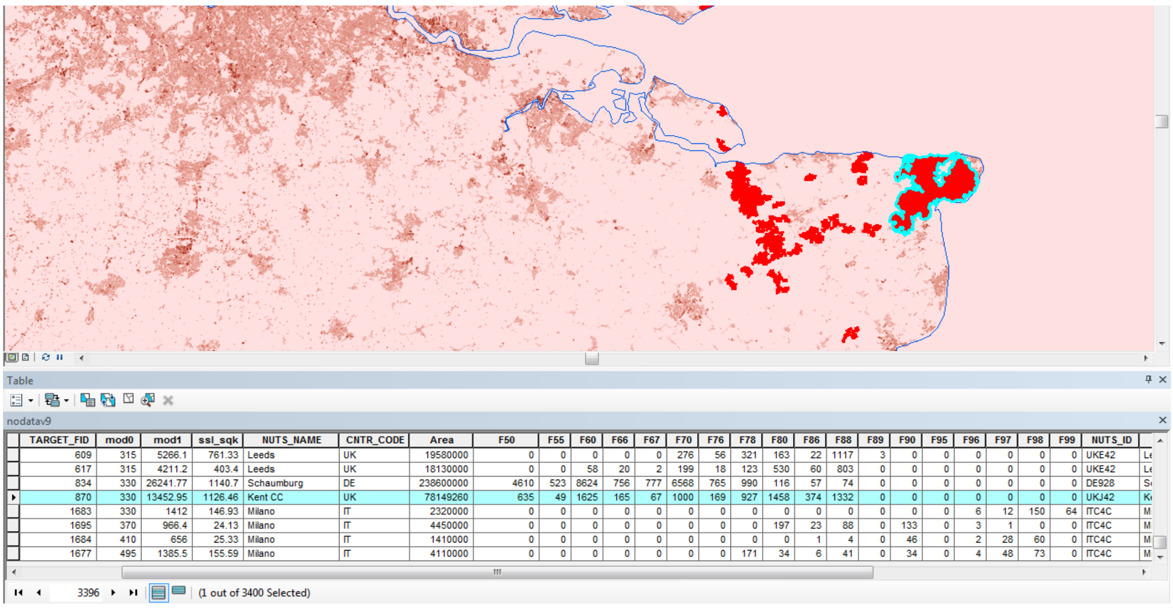
The problem of the gap has been addressed by considering more indicators to analyze the effects from different angles and implications, the characteristics of the data lost and to be able to sort them based on a an importance criteria.
The indicators used for the estimation and sorting are:
Area of gap
SSL sum in the gap
TSL e QSL (Typology or diversity and Quantity of settlement lost) in the gap

The area measures the extent of missing data regardless of their characteristics as mentioned above has a maximum of 741 km2, a minimum of 1km2 and a total of about 17,000 km2
The sum of the values of the SSL in each gap allows to identify the amount of data lost SSL in relation to the place where the gap is present and being the same SSL a good proxy for the estimation of the built-up such an indication from an estimate more 'specification of error.
The indicators TSL and QSL derived using settlement classification layer, instead try to interpret the categories, types of settlement lost to associate the quantity is also a type (XL, L, M, S)
The TSL to each category of pixels lost associates a different weight, which is then added in the area of the gap:

Weighted sum of the no data pixel (weight base on the settlement class layer): P1 (50) = 1, P2(55) = 1.1, P3(60) = 1, P4(66) = 1.12, P5(67) = 1.15, P6(70) =1, P7(76) = 1.8, P8(78) = 2.2, P9(80) =1.2, P10(86) = 3, P11(88) = 3.5, P12(89) = 4, P13(90) = 2.5, P14(95) = 4.5, P15(96) = 5, P16(97) = 5.5, P17(98) = 6, P18(99) = 6.5

The QSL count the number of typology lost in a gap:
Weighted sum of the SQLdistinct(settlement class) overlay by the nodata object: P1 (50) =5, P2(55) = 10, P3(60) = 15, P4(66) = 20, P5(67) = 25, P6(70) =30, P7(76) = 35, P8(78) =40, P9(80) =45, P10(86) = 50, P11(88) = 55, P12(89) = 60, P13(90) = 65, P14(95) = 70, P15(96) = 75, P16(97) = 80, P17(98) = 85, P18(99) = 90

The indicators described and shown to the customer are used to prioritize the search for alternative images in areas where the lack of information would produce more 'discomfort. In conclusion, the choice was addressed on use of' indicator QSL.




| TARGET_FID | mod0 | mod1 | ssl_sqk | NUTS_NAME | CNTR_CODE | Area | F50 | F55 | F60 | F66 | F67 | F70 | F76 | F78 | F80 | F86 | F88 | F89 | F90 | F95 | F96 | F97 | F98 | F99 | NUTS_ID |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 609 | 315 | 5266.1 | 761.33 | Leeds | UK | 19580000 | 0 | 0 | 0 | 0 | 0 | 276 | 56 | 321 | 163 | 22 | 1117 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | UKE42 |
| 617 | 315 | 4211.2 | 403.4 | Leeds | UK | 18130000 | 0 | 0 | 58 | 20 | 2 | 199 | 18 | 123 | 530 | 60 | 803 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | UKE42 |
| 834 | 330 | 26241.77 | 1140.7 | Schaumburg | DE | 238600000 | 4610 | 523 | 8624 | 756 | 777 | 6568 | 765 | 990 | 116 | 57 | 74 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | DE928 |
| 870 | 330 | 13452.95 | 1126.46 | Kent CC | UK | 78149260 | 635 | 49 | 1625 | 165 | 67 | 1000 | 169 | 927 | 1458 | 374 | 1332 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | UKJ42 |
| 1683 | 330 | 1412 | 146.93 | Milano | IT | 2320000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 12 | 150 | 64 | ITC4C |
| 1695 | 370 | 966.4 | 24.13 | Milano | IT | 4450000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 197 | 23 | 88 | 0 | 133 | 0 | 3 | 1 | 0 | 0 | ITC4C |
| 1684 | 410 | 656 | 25.33 | Milano | IT | 1410000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | 0 | 46 | 0 | 2 | 28 | 60 | 0 | ITC4C |
| 1677 | 495 | 1385.5 | 155.59 | Milano | IT | 4110000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 171 | 34 | 6 | 41 | 0 | 34 | 0 | 4 | 48 | 73 | 0 | ITC4C |

*Figure 26 - Cloud mask database*

The figure 27 shows the result of the integration. In the first horizontal line of images, in red, the area covered by clouds; in the second line the built-up recovered; in the third line the final mosaic.

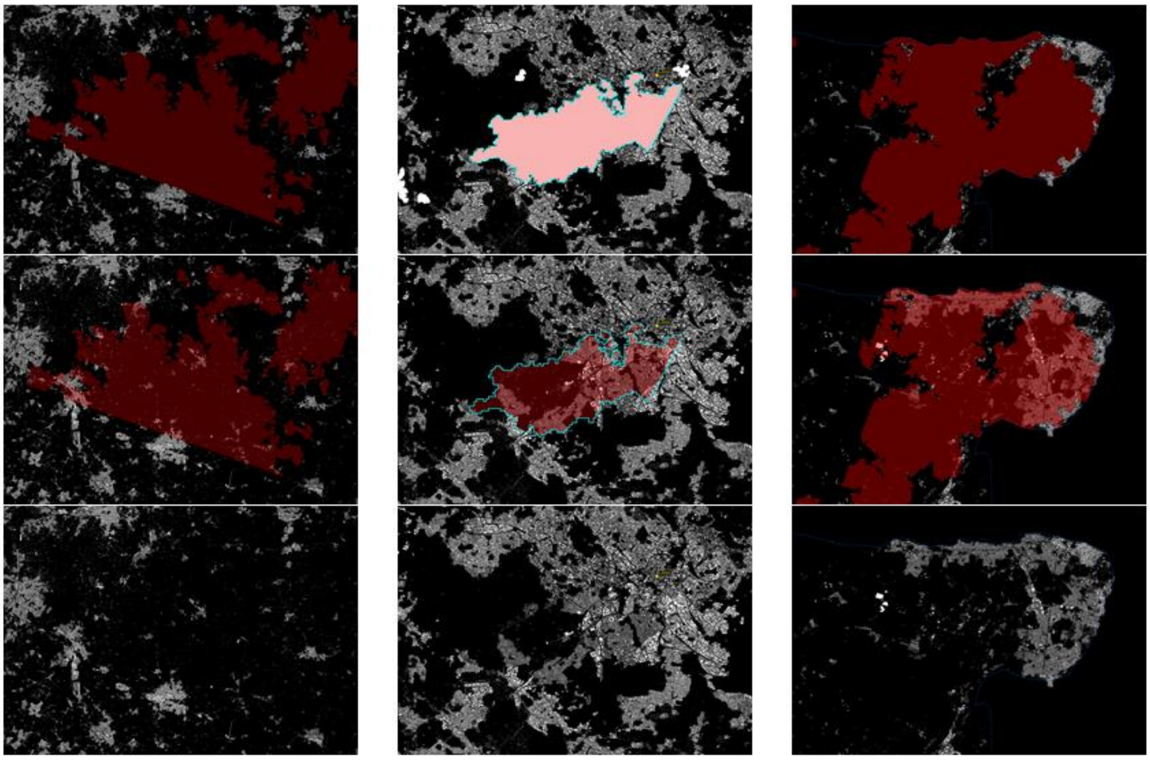


Figure 27 - Integration with other images

### The use of Open Street Map Vector Building

Despite having a large amount of images, same areas remain uncover or unrecoverable. In figure 28 the example of a gap in Milano. The scene over Milano has big compact cloud in the center of the city, plus small cloud around it. Looking into the JRC satellite repository were not find alternative VHR images so we went looking other alternatives. The OpenStreetMap database already used to mask the street network [8], in Milano has also the building footprint. That OSM building footprint dataset converted in a service were included in the post processing and added to final images (see figure 28)

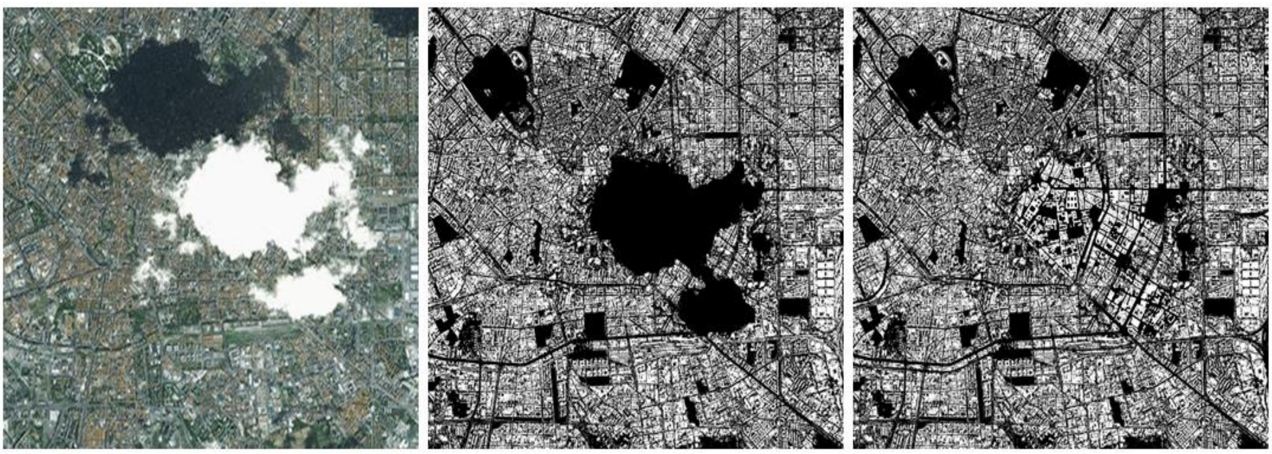


Figure 28 - OSM building integration

# Conclusions

- 3800 Input scenes with a resolution of 2.5m
- Average size of a scene in km: 75km x 75 km
- 10,337,122,313,105 pixels processed
- 55 Countries covered
- 5,947,006 square km of land mass classified
- 85,000 square km of built-up detected.

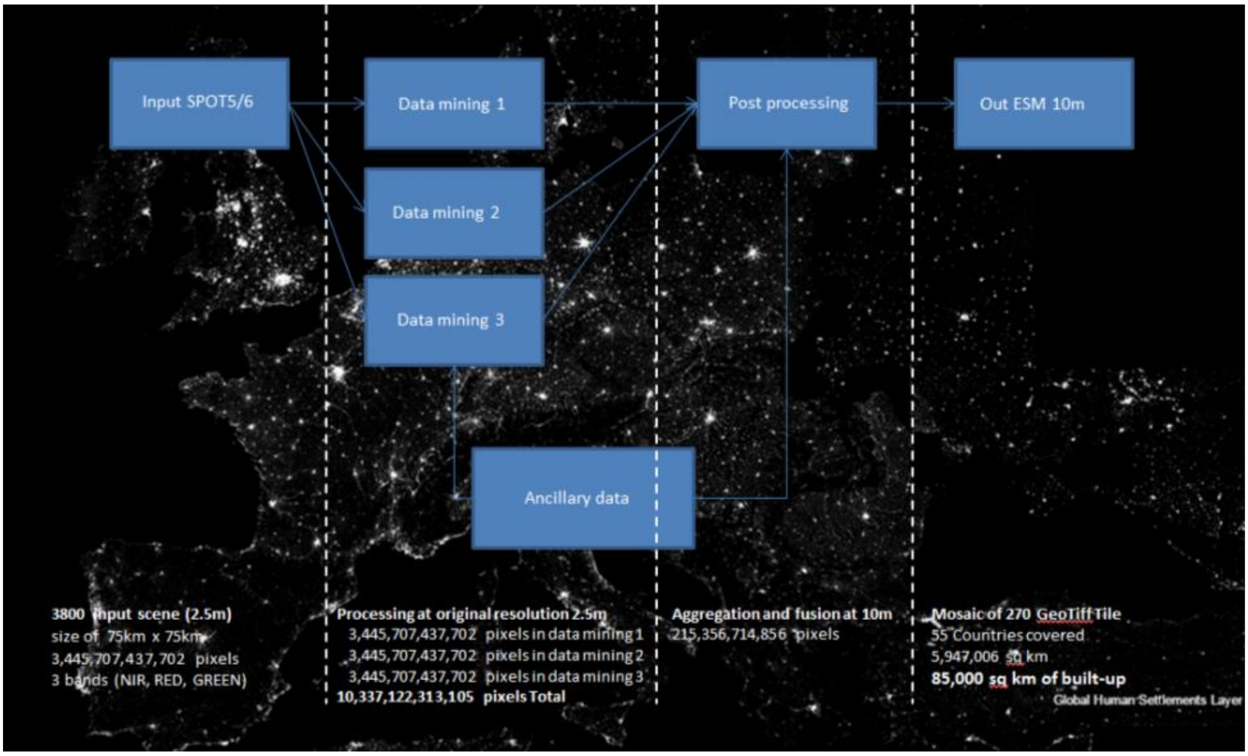



*Figure 29 - ESM in numbers*

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